

Lidar Measurements of Relative Humidity and Ice Supersaturation in the Upper Troposphere

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ABSTRACT

We compute upper tropospheric relative humidity profiles using water vapor profiles measured by an airborne DIAL and a ground-based Raman lidar. LASE water vapor and MTP temperature profiles acquired from the NASA DC-8 aircraft during the recent Pacific Exploratory Mission Tropics B (PEM Tropics B) field mission in the tropical Pacific and the SAGE-III Ozone Loss and Validation Experiment (SOLVE) in the Arctic as well as water vapor profiles derived from the ground-based DOE ARM Southern Great Plains (SGP) CART Raman lidar are used. Comparisons of the lidar water vapor measurements with available in situ measurements show reasonable agreement for water vapor mixing ratios above 0.05 g/kg. Relative humidity frequency distributions computed using LASE data indicate that ice supersaturation occurred about 5-11% of the time when temperatures were below -35°C. While a higher frequency of ice supersaturation was observed during SOLVE, higher peak values of relative humidity were observed during PEM Tropics B. The relative humidity fields associated with cirrus clouds are also examined.

1. Introduction

Accurate measurements of upper tropospheric relative humidity are important for initializing numerical weather models, computing shortwave and longwave radiation fluxes and cooling rates, forecasting the formation of aircraft contrails, and understanding and modeling ice nucleation in cirrus clouds. Predicting the formation and persistence of cirrus clouds in particular requires accurate measurements of ice supersaturation at high altitudes and corresponding cold temperatures. Recent measurements by in situ sensors on radiosondes and aircraft have shown that large ice supersaturations may exist at low temperatures in both clear and cloudy conditions [1,2]. Since ice supersaturation often occurs in thin layers, the fraction of the upper troposphere where supersaturation exists may be considerably larger than deduced from in situ measurements, which suggests that the fraction of sky covered by optically thin cirrus clouds in moderately supersaturated regions can be large [2].

Both airborne and ground based lidars can provide additional high spatial and temporal resolution measurements to help quantitatively assess the frequency and location of these ice supersaturation regions and their relationship to ice clouds. Two lidar systems have been used for these investigations. The Lidar Atmospheric Sensing Experiment (LASE), which has most recently flown on the NASA DC-8 aircraft, measured water vapor, aerosol, and cloud profiles over the tropics during the Convection and Moisture Experiment-3 (CAMEX-3) and Pacific Exploratory Mission Tropics B (PEM Tropics B) missions, and over the polar regions during the SAGE-III Ozone Loss and Validation Experiment (SOLVE). The ground-based Cloud and

Radiation Testbed (CART) Southern Great Plains (SGP) Raman lidar, which has been operated by the Department of Energy Atmospheric Radiation Measurement (ARM) program, has routinely measured water vapor, aerosol, and cloud profiles over the SGP site in northern Oklahoma. We discuss these lidar systems, describe their water vapor and cloud profile measurements, and show how they have been used to assess relative humidity and ice supersaturation in the upper troposphere.

2. Instrumentation

LASE is an airborne DIAL (Differential Absorption Lidar) system that was developed to measure water vapor, aerosols, and clouds throughout the troposphere [3,4]. This system uses a double-pulsed Ti:sapphire laser, which is pumped by a frequency-doubled flashlamp-pumped Nd:YAG laser, to transmit light in the 815-nm absorption band of water vapor. LASE operates by locking to a strong water vapor line and electronically tuning to any spectral position on the absorption line to choose the suitable absorption cross-section for optimum measurements over a range of water vapor concentrations in the atmosphere. For the DC-8 missions listed above, LASE operated using strong and weak water vapor lines in both the nadir and zenith modes, thereby simultaneously acquiring data both above and below the aircraft. LASE simultaneously measures aerosol backscattering profiles at the off-line wavelength near 815 nm. Typical horizontal and vertical resolutions for water vapor profiles extending between 0.2-14 km are 14-70 km (1-3 min) and 300-900 m, respectively. Comparisons of water vapor measurements made by airborne dew point and

frost point hygrometers, NASA/GSFC Raman lidar, and radiosondes showed the LASE water vapor mixing ratio measurements to have an accuracy of better than 6% or 0.01 g/kg, whichever is larger, across the troposphere [5]. Profiles of the total scattering ratio, defined as the ratio of total (cloud+aerosol+molecular) scattering to molecular scattering, are determined by normalizing the scattering in the region containing enhanced aerosol scattering to the expected scattering by the "clean" atmosphere at that altitude. These aerosol measurements, which span the altitude range between 0.03-18 km, typically have horizontal and vertical resolutions of 200 m and 30 m, respectively.

During the PEM Tropics B and SOLVE missions, temperature profiles were provided both above and below the aircraft by the DC-8 Microwave Temperature Profiler (MTP). The MTP is a radiometer that passively measures the thermal emission from oxygen molecules at 3 frequencies between 55 and 59 GHz -- each at 10 elevation angles; these 30 measurements of brightness temperatures are then used to retrieve a temperature profile. The vertical resolution of the retrieved profiles is approximately 100 m near the aircraft and degrades with distance. Vertical resolution should have little effect on the PEM Tropics B measurements since there is little structure in tropical temperature profiles below the tropopause (~16-17 km); it is more of an issue for the SOLVE measurements, but in this case the aircraft was generally close enough to the tropopause that the structure could be adequately resolved. For a nominal flight altitude of 10 km, the rms error in the MTP retrieved temperature profile is <1 K within 2 km of the aircraft, and degrades to <2 K within 5 km. Relative humidity profiles are computed using LASE water vapor profiles and MTP temperature profiles.

The CART Raman Lidar (CARL) uses a tripled Nd:YAG laser, operating at 355 nm with 400 millijoule pulses at 30 Hz. A 61-cm diameter telescope collects the light backscattered by molecules and aerosols at the laser wavelength and the Raman scattered light from water vapor (408 nm) and nitrogen (387 nm) molecules. These signals are recorded with a vertical resolution of 39 meters. A beam expander reduces the laser beam divergence to 0.1 mrad, thereby permitting the use of a narrow (0.3 mrad) as well as a wide (2 mrad) field of view. The narrow field of view, coupled with the use of narrowband (~0.4 nm bandpass) filters, reduces the background skylight and, therefore, increases the maximum range of the aerosol and water vapor profiles measured during daytime operations.

Water vapor mixing ratio profiles are computed using the ratio of the Raman water vapor signal to the Raman nitrogen signal. Relative humidity profiles are computed using the lidar water vapor mixing ratio profiles and the temperature profiles derived from the Atmospheric Emitted Radiance Interferometer (AERI) retrievals and Rapid Update Cycle (RUC) model. The CARL water vapor mixing ratio profiles and precipitable water vapor (PWV) retrievals are calibrated using the coincident nighttime measurements of precipitable water vapor (PWV) from the microwave radiometer (MWR) [6]. Profiles of total scattering ratio are derived using the Raman nitrogen signal and the signal detected at the laser wavelength. Aerosol volume backscattering cross section profiles are then computed using the aerosol scattering ratio

and molecular scattering cross section profiles derived from atmospheric density data.

3. LASE Measurements

During PEM Tropics B, LASE measured a total of about 104 hours of water vapor, aerosol, and cloud profiles over 18 science flights between March 6 and April 18, 1999. MTP measured temperature profiles on 13 of these flights, so that about 73 hours of relative humidity profiles were computed using LASE water vapor and MTP temperature data. These flights generally occurred over the tropical Pacific Ocean between 10°N and 30°S and 170°E and 90°W. Because of near field signal effects associated with the incomplete overlap of the laser beam and telescope field of view, LASE can not retrieve water vapor profiles within about 1 km above and below the aircraft. Therefore, in order to derive continuous tropospheric water vapor profiles for altitudes between 0.5-14 km during PEM Tropics B, in situ water vapor measurements collected by cryogenic and laser diode hygrometers on the DC-8 were used to interpolate between the LASE nadir and zenith water vapor profiles. Approximately 62 hours of relative humidity profiles were computed using LASE water vapor and MTP temperature profiles measured during the first 8 science flights of the first SOLVE deployment. These flights were over the Arctic region between 70°N and 85°N and between 40°W and 85°E and occurred between November 30 and December 16, 1999. Since the DC-8 generally flew above the tropopause at altitudes between 10-12 km, LASE nadir measurements provided complete water vapor, aerosol, and cloud profile coverage throughout the troposphere.

Figure 1 shows examples of relative humidity (ice) (RHI) and cloud profiles derived from LASE and MTP data acquired between 02:00 to 05:00 UT on April 14, 1999 during the transit flight from Tahiti to Easter Island. Cirrus clouds were observed both above and below the aircraft during the flight as shown by the LASE total scattering ratio profiles. The aircraft also flew through cirrus clouds between 04:20-04:40 UT during this flight. The cryogenic and laser diode in situ sensors on the DC-8 indicated ice supersaturation conditions occurred during these in-cloud periods. The relative humidity profiles derived from LASE and MTP showed ice supersaturation occurred predominantly above the aircraft. The temperature at flight level (~10.2 km) was about -35°C. Figure 1 also shows a comparison of the relative humidity profiles derived from the ECMWF model along this same flight path. The model generally represents the large-scale humidity variations along the path, but misses the small scale, high relative humidity conditions near the cirrus clouds.

Frequency distributions of relative humidity and temperature constructed using the RHI and temperature profiles derived from the LASE and MTP measurements acquired during the PEM Tropics B and the first SOLVE deployments are shown in Figure 2. The SOLVE distributions in Figure 2 were constructed using preliminary LASE and MTP data; final distributions will be constructed after completion of the SOLVE mission and presented in this paper. These distributions were constructed using 1°C and 1% RH bin sizes. Note the change in scales from logarithmic

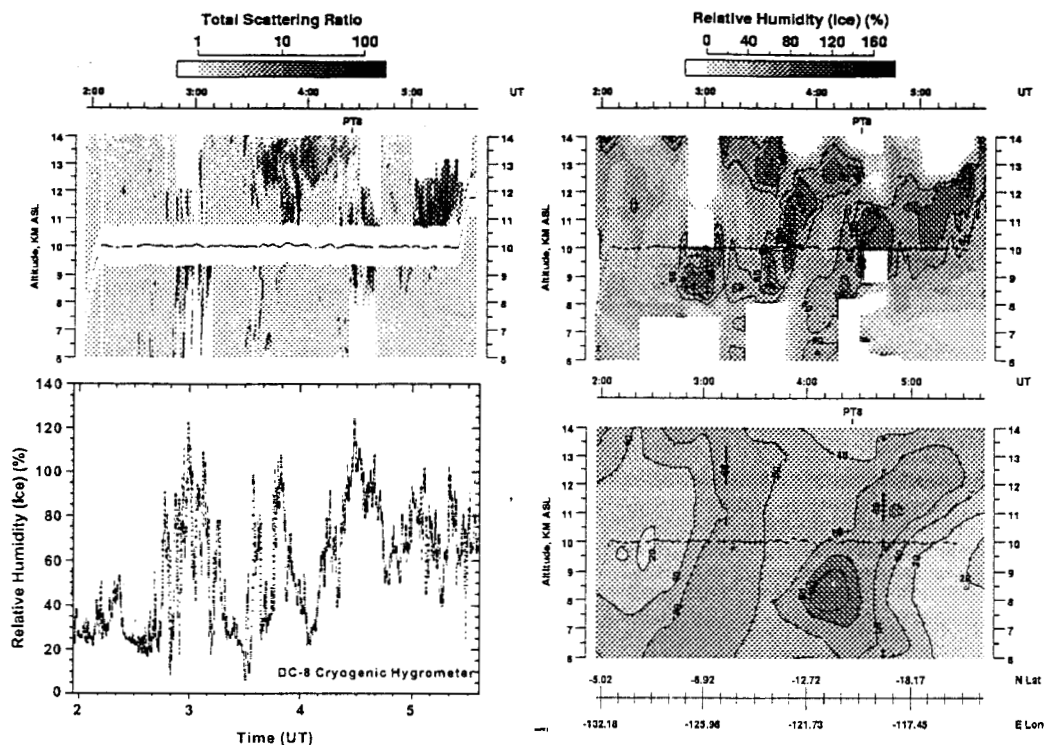


Figure 1. (Top left) Total scattering ratio and (top right) relative humidity (ice) profiles derived from LASE measurements acquired on April 15, 1999. (Bottom left) Relative humidity derived from DC-8 in situ cryogenic hygrometer. (Bottom right) ECMWF model relative humidity profiles during the same period. The solid line in the images represents the aircraft flight altitude. These images cover a horizontal distance of about 2900 km.

to linear from the PEM Tropics B to SOLVE results. These distributions show that ice supersaturation conditions occurred about 5% and 11% of the time during PEM Tropics B and SOLVE, respectively, and are consistent with the range of between 5-20% derived using in situ sensors on commercial and research aircraft [2]. The lower frequencies of ice supersaturation derived from the LASE and MTP data during PEM Tropics B are likely due to two reasons. First, the LASE water vapor retrievals were generally limited to altitudes below 14 km and, therefore, did not sample the region near the tropical tropopause where thin cirrus were often observed. Second, the PEM Tropics B flight tracks were often designed to avoid clouds to optimize lidar profiling of ozone and water vapor. Figure 2 also shows that higher ice supersaturation values were observed during PEM Tropics B than during SOLVE. These higher values may be associated with different aerosol properties (e.g. fewer aerosol sources and/or removal of aerosols via fallout of previously-formed ice crystals) associated with the tropical "maritime" environment [1].

4. Raman Lidar

Profiles of water vapor mixing ratio, relative humidity, total scattering ratio, aerosol and cloud backscatter, and depolarization ratio have been computed from CARL on a nearly continuous basis from April, 1998 through the present time. During this period, CARL operated nearly 50% of the time. CARL measurements of cirrus and upper tropospheric

relative humidity are limited to nighttime because the increased daytime solar background limits water vapor retrievals to altitudes below about 4 km. Examples of these profiles acquired during the night of December 5, 1998 are shown in Figure 3. These measurements show ice supersaturation occurred near the cirrus clouds throughout much of this night. We shall discuss these and other CARL measurements in more detail at the meeting.

5. Summary

Upper tropospheric relative humidity profiles computed using airborne LASE and ground-based SGP CART Raman lidar show ice supersaturation occurs in both clear and cloudy regions. LASE data acquired during the PEM Tropics B and first SOLVE deployments indicate that ice supersaturation occurred about 5-11% of the time when temperatures were below -35°C . These results do not indicate that in situ measurements significantly underestimate the fraction of the upper troposphere where supersaturation exists. However, since ice supersaturation often occurs in thin layers, the large vertical (~ 300 to 900 m) and horizontal (~ 14 to 70 km) resolutions of the LASE water vapor data may not fully capture the peak RHI values and, therefore, may underestimate the frequency and magnitude of ice supersaturation. Additional studies will be performed to investigate how the vertical and temporal resolutions of the LASE water vapor measurements affect the derived frequency of ice supersaturation.

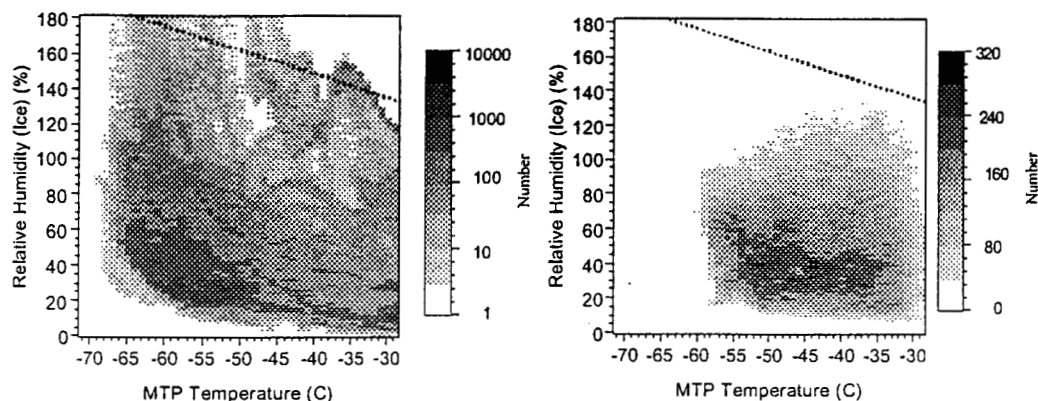


Figure 2. Distribution of relative humidity (ice) as a function of temperature derived using LASE water vapor and MTP temperature profiles measured during PEM Tropics B (left) and first SOLVE deployments (right). The SOLVE results are computed using preliminary data. The dotted lines represent water saturation.

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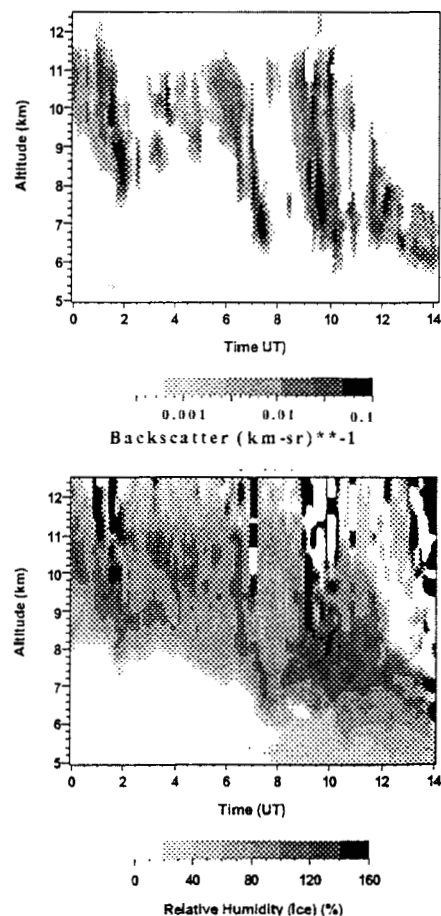


Figure 3. Cloud backscatter (top) and relative humidity (bottom) profiles measured by the SGP CART Raman lidar on December 5, 1998.